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RESEARCH ARTICLE

Review of studies on motor-manual felling productivity in eucalypt stands

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Abstract

Globally, about 20 million ha of land area is occupied by plantations of *Eucalyptus*. Motor-manual tree harvesting techniques (using chainsaws) are still applied in eucalypt plantations, especially in difficult terrains or for large- sized trees where mechanised felling may not be an effective and safe possible option to apply. There is little information available on motor-manual felling in eucalypt stands. This article reviewed available literature on the productivity of motor-manual felling. The results were classified into four regions, including Africa, Asia/Oceania, America and Europe. Results of international studies indicate that the main factors impacting the productivity of motor-manual felling include diameter at the breast height (DBH), travelling distance to trees, understory density and terrain slope. Operator experience also plays a key role in felling operations. The range of reported productivity varied from 0.6 m^3/PMH_0 to 48.9 m^3/PMH_0 in different regions. This article provides key recommendations on improving motor-manual felling productivity, which can provide a guide for sustainable harvesting planning purposes.

Keywords

Motor-manual felling, Productivity, Time study, Work cycle, Tree volume, Eucalypt

Introduction

Ferreira et al. (2019) reported that about 20 million ha of global land area has been occupied by plantations of *Eucalyptus* as of 2009. Most of these plantations are located between 35°S and 35°N, which suggests that they are fast-growing plantations in the southern hemisphere. Plantations of *Eucalyptus* have a growth rate higher than 10 m^3

per year per ha which might enable them to become one of the sources to produce pulp-wood, sawlog, wood chips and fuel wood (Ferreira et al., 2019). According to Spinelli et al. (2009), harvesting operations in plantations of *Eucalyptus* should be optimised to make the cost of wood fibre production competitive. Motor-manual tree harvesting techniques (using chainsaws) are still applied in eucalypt plantations, especially in difficult terrains (including steep slopes and/or excessive ground obstacles) or areas with large trees, where mechanised felling (e.g. using feller-bunchers and harvesters) may not be an effective nor safe option to apply. As there is little information available on motor-manual felling in eucalypt stands, this article aimed to review available literatures on the work productivity evaluation of motor-manual felling operations. This review could provide a guide on productivity management of felling operations for the academic and industrial users.

Materials And Methods

Work productivity for motor-manual felling

Tree felling is an important component of the harvesting operations (Conway, 1982). Felling and bucking may be carried out manually, motor-manually or through using mechanised harvesters and feller-bunchers (Conway, 1982). One of the common ways to study the economics of felling operations are time studies and productivity evaluation. According to Magagnotti et al. (2012), in a simple work study one may focus on mass output and time input. The direct relationship between product output and time input is called productivity. The variables affecting the productivity may include various factors, such as technology, work technique, operator skill and environmental conditions. Some of these variables can be managed, while others passively received. Time consumption measurements may be conducted at the plot level, work shift level, work cycle or elemental level (Magagnotti et al., 2012). The information created by time studies can be useful for production scheduling, budgeting and in comparisons of alternative procedures and equipment (Murphy, 2005).

The chainsaws are common equipment for motor-manual felling. Past studies have confirmed that ground (e.g. terrain class) and soil conditions (e.g. slope), understory density, tree dimensions (e.g. Diameter at Breast Height (DBH)), species, number of trees per ha, cutting technique/ experience of operators, felling type (clear cut, systematic, selective thinning), felling intensity, stand type (evenly-aged high forest, coppice, etc.), weather conditions and distance between trees can impact on the productivity of motor-manual felling (Sobhani, 1984; Peterson, 1987; Food and Agriculture Organization (FAO), 1998; Hartsough et al., 2001; Kleunder, Stokes, 1996; Wang et al., 2004; Ghaffariyan, Sobhani, 2007; Magagnotti et al., 2012; Balimunsi et al., 2011; Balimunsi et al., 2012; Borz, Ciobanu, 2013; Ignea et al., 2017; Acosta et al., 2018). It should be noted that felling is one of the riskiest components of harvesting operations. The safety of the felling crew should be always considered by the forest-harvesting planners (Dykstra, Heinrich, 1996).

This article aimed to review the available studies on productivity of motor-manual felling in eucalypt plantations. The other objective was to provide detailed information on factors affecting the productivity and the root cause of working delays. Only studies that reported all the required information were included in this review. According to some of the previous studies (e.g. Han, Renzie, 2005), species can impact on the productivity of motor-manual felling as different species may have various tree characteristics, such as wood density, branchiness, tree form, growth, crown size, crown shape, etc., which in turn may influence the performance of felling and processing tasks. From industrial point of view, most of the managers of Australian forest and plantations prefer to separate the harvesting productivity studies in eucalypt stands from pine stands due to differences in the requirements in silvicultural and management strategies and techniques (such as skidding productivity in coniferous stands reported by Ghaffariyan (2020a) and general productivity predicting models for skidders working in eucalypt stands by Ghaffariyan (2020b)

Motor-manual tree felling studies in eucalypt plantations

The literature data were obtained through online journal papers and technical reports published in English language by searching electronic databases including Google Scholar, Scopus and Web of Science. The keywords used in the searches included motor-manual felling, chainsaw, productivity, time study and eucalypt plantations. The reviewed reports on eucalypt manual felling were organised based on the four main geographical regions (Africa, Asia/Oceania, America and Europe).

Results

Africa

Dos Santos et al. (2014) studied the efficiency of tree felling (Fig. 1) in the Arusha Region of Tanzania. The study area contained species such as *Eucalyptus* sp. mixed with other hardwood and softwood species. Two-man cross cuts chainsaws (model type not reported) were applied to fell the trees. Wood extraction from the stand to the roadside was performed using oxen and farm tractors. Two groups of workers were studied, including start-ups (with no work experience) and experienced ones (who had working experience in felling operations longer than 8 years). The measured variables included stump diameter, DBH, tree height, number of logs per tree, log length, number of trees per day and terrain slope (descriptive statistics were not reported). Dos Santos et al. (2014) recorded a productivity of the experienced workers of 7.7 cubic meters per delay- free productive machine hours (m^3/PMH_0), while the productivity of start-up workers averaged at 6.2 m^3/PMH_0. The variables DBH and number of logs affected significantly the work productivity. Dos Santos et al. (2014) added that the skills and work experience of the operator could be among the other factors influencing felling productivity.

Asia and Oceania

Manavakun (2014) studied the harvesting operations in eucalypt plantations in Thailand, where the estimated area of plantations of *Eucalyptus* sp. varied from 480,000 ha to 600,000 ha with a rotation period of five years. Eucalypt plantations have been also established in China and Papua New Guinea. Common species are *E. camaldulensis, E. tereticornis* and *E. urophylla*. In places where relatively low-cost labour is available, motor-manual felling is still applied. Unlike mechanised felling operation, large capital costs are not required to run the motor-manual felling due to the low purchase price of chainsaws. Motor-manual felling provides more jobs than mechanical felling for local people as it is a labour-intensive operation (Manavakun, 2014). Brush saws (Fig. 2) are applied more than chain saws for cutting small trees in Thailand. Trees are felled and processed manually then extracted using a farm tractor (which is equipped with a loading grapple) to the trucks at roadside for transportation. In some areas, the processed logs might be manually loaded to the trucks in the stands.

The felling work cycle included elements such as walking, cleaning, determining direction of felling, undercut and back cut (Manavakun, 2014). Bucking included four elements: walking, cleaning, delimbing and bucking. The delimbing phase consisted of walking, marking and delimbing. Regression models were developed by Manavakun (2014) to predict the felling time per each work cycle. According to these models, the stump diameter and travel distance to the tree were impacting significantly on the felling productivity. In addition, the log diameter and walking distance between logs were other variables significantly affecting the bucking productivity. The delimbing produc-

Figure 1. Motor-manual felling in eucalypt plantations in South Africa (Little et al. 2010)

Figure 2. Cross cutting with brush saw in Thailand (Manavakun, 2014)

tivity was significantly impacted by the travelling distance to tree and DBH. Depending on different work combinations, productivity (of work including felling, bucking, delimbing, stacking and loading) varied from 1.7 m^3/PMH_0 to 4.1 m^3/PMH_0 for an average stem size of 0.13 m^3. Working delays of felling operation were 12% of the total time, which included time spent for refuelling, lubrication, sharpening the saw and maintenance (Manavakun, 2014). Engler et al. (2012 and 2016) reported that eucalypt plantations were established in the south of China, which covered 2.6 million ha (Zhao, 2011). The harvesting operation was mainly carried out manually by the workers. Chains saw is a conventional tool for felling trees in China. Engler et al. (2012) indicated that their study area located in the Guangxi Province was steep with slopes ranging from 20% to 52%. The stands were mixed and included *Eucalyptus grandis* x *urophylla* and *Mytilaria laosensis*. The age of eucalypt trees in the study area varied from 3 years to 9 years, with a DBH ranging from 9.4 cm to 16.4 cm, which resulted in an average productivity of 0.6 m^3/PMH_0 (chain saw model/type was not reported). In the regression model, DBH was a significant factor affecting the working time. Engler et al. (2012) included hauling logs by hand to the roadside in addition to the time spent for felling activities (including removing grass, felling, debranching, measuring logs and bucking).

In Oceania, there are about 132 million ha of Australian native forests which are mainly covered by eucalypt and acacia forests (Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), 2018). Mechanised harvesting systems are dominant to utilise the forests and plantations in Australia. According to Acuna (2010), the motor-manual felling is limited due to its high risk of associated fatalities and accidents. Tasmania is a state located in the southern part of Australia, where 67% of its forests are made of eucalypt (Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), 2018). Native Tasmanian eucalypt forests are established in steep, rocky, rough and un-even terrains with relatively large tree sizes (Acuna, 2010). In such conditions, the manual felling may still play a role when mechanised felling machines may not be able to reach to the trees and/or operate safely due to the difficult terrain and stand conditions (Connell, 2003). Neyland et al. 2009 indicated that old-growth trees require manual felling due to their size. The productivity of motor-manual felling was studied by Ghaffariyan, Acuna (2010) in native eucalypt stands in Tasmania. The native stands composed of various species, such as *E. amygdalina, E. pulchella, E. tenuiramis, E. obliqua, E. globulus* and others. A Stihl 066 chainsaw was used to fell and process trees into logs by one operator. The average DBH was 41.3 cm, while the tree volume averaged at 1.5 m^3. The study reported an average productivity of 48.9 $m^3/PMH_{0,}$ owing to the large size of felled trees in the research area. DBH significantly impacted the productivity according to the regression model. Under cut and back cut had the largest share of working elements (31% and 28% of the total working time, respectively). For large trees, the chainsaw operator needed to use the wedge to fell the trees in the desired direction (5% of total working time). The other work elements included move-clean (11%), fuelling (9%) and debranching (2%). The operational delay was 29% of the working time, in which the operational delays covered 26% of the working time during motor-manual felling. The operational delays were mostly caused by waiting for the skidder, which extracted the trees from the felling site to the landing places.

America

Short-rotation eucalypt plantations regenerate after harvesting using natural regeneration, artificial regeneration and coppice growth. Natural regeneration using seeds may not be a suitable method for short rotations of *Eucalyptus grandis* or *E. saligna*. When seedlings are grown in a nursery and artificial planting is applied, then there is a requirement for the intensely silvicultural practices (United States Department of Agriculture (USDA), 1992). According to Geary (1983), after felling eucalypt trees, new stems which are called coppice often grow from the stumps. Growing this type of crops (such as *Eucalyptus grandis* grown in Florida (USA) or in South Africa) would help with replanting. The most suitable type of coppice is the one produced in spring using chainsaw with the low level of damage to the stumps, barks and roots. (Geary, 1983). Motor-manual felling can be combined with the ground-based skidding on flat and moderate terrains or with the cable yarding in steep slopes. USDA (1992) reported that the cable yarding system was used to harvest the eucalypt stands in Hawaii. The main advantage of this system was the low rate of damage to the site and residual stands. The trees were felled manually with the chain saws and were then extracted to the roadside by the yarder (productivity estimates were not mentioned in the report by USDA (1992)).

Brazil has a strong plantation industry. Eucalypt species were introduced into Brazil for the forestry purposes in the early 1900s. The area of eucalypt plantations is over 6 million hectares and yields 184 million m^3 of round wood annually. Efficient harvesting of the short rotation eucalypt stands is a challenge which requires further developments (FAO, 2009; Couto et al., 2011; Guerra et al., 2016). Malinovski, Piovesan (2000) studied the chainsaw productivity in plantation of *Eucalyptus* using clear felling in a mountainous area located in the Vale do Rio Doce Region, Minas Gerais, Brazil. The shortwood cutting method was used. The data were collected from October 1995 to February 1996. The study included 29 chainsaw operators (chainsaw model was not identified in the source). Felling productivity varied from 8.0 m^3 per day to 13.1 m^3 per day (assuming 6 hours of productive time per day, this is equal to 1.3 m^3/PMH_0 to 2.2 m^3/PMH_0). The worker age, working experience, triceps/body fat composition (%) and body mass index (weight/height) were the significant variables impacting on the productivity. Malinovski, Piovesan (2000) reported that an experienced young worker with the mesomorphic-endomorphic characteristics could be the best operator type to fit to the work conditions in the mountainous areas resulting in a higher productivity. Another case study was carried out by Fernandes et al. (2013) in an evenly aged stand of eucalypt plantation. Felling work teams consisted of two workers including an operator and a helper. The average felling cycle time was 2.5 minutes per tree, which resulted in a productivity of 5.2 m^3/PMH_0. Leite et al. (2014) found that the wider tree spacing (with larger tree size), the higher the chainsaw productivity. Their study area was in a first rotation eucalypt plantation where the average ground slope was 49%. The work team included an operator and a helper who used Stihl360 chainsaw. In the study plot where the spacing was 3 x 2.5 m and tree volume averaged at 0.33 m^3, the mean productivity for felling and processing was reported at 4.7 m^3/PMH_0. For the 3 x 3.33 m spacing (tree size of 0.36 m^3), the average productivity was 5.2 m^3/PMH_0. For the study plot with spacing of 3 x 4 m spacing (tree size of 0.37 m^3), the productivity was 5.73 m^3/PMH_0.

Carey et al. (2018) reported that young eucalypt trees were harvested as the source of biomass in Central Chile. Their study area was in the Las Palmas Region. The stand was a plantation of *E. globulus* (planted in 2004), mixed with *Acacia melanoxylon* which naturally regrew in the study area. The average slope was 13%, the average DBH was 15.7 cm, while stem volume averaged at 95.1 m^3 per ha (average tree size was 0.12 m^3). The young stands were harvested using a motor-manual felling system. A Stihl MS 360 chain saw was used to fell the trees and to stack them in the bundles. Then the bundles were skidded to the roadside by oxen in manual harvesting, while the skidder extracted the bundles within semi-mechanised harvesting. Based on the study results, the utilisation rate was low: about 64% for the manual harvesting. The personal delay was about 20.8% of the schedule time, which was spent as rest time taken by the operators. The average felling productivity of the manual method was 1.2 $m^3/PMH_{0,}$ while the felling productivity for the semi-mechanised system averaged at 1.3 m^3/PMH_0 (note that Carey et al. (2018) reported productivity in Mg_w thus a factor of 1:1 was assumed to convert Mg_w to m^3). The study results confirmed that when the understory density increased, the felling productivity decreased due to the longer time required for movement, etc. When slope was larger than 20%, then the work productivity diminished by 39%.

Europe

According to Gonzales-Garcia et al. (2009), Spain is a major forest country. Roughly, 46% of the total wood demand is satisfied by its own forest industry. Eucalypt wood is extensively used for paper pulp manufacture in Spain, Portugal and Brazil. *Eucalyptus globulus* is the most important species in South-Western Europe and specifically in Spain. No thinning is carried out and the stands are only treated in the final cutting. For final cuts, firstly trees are felled using a chainsaw (no productivity record was reported by Gonzales-Garcia et al. (2009)) to open space for the harvesters. The mechanised harvesters are then applied to fell and process trees to logs, which are then extracted to the roadside by the forwarders. Table 1 summarises the motor-manual productivity case studies reviewed in this article.

Conclusions

Motor-manual felling operations are more time consuming as compared with the mechanised operations (Manavakun, 2014). Available literature indicated that DBH (Ghaffariyan, Acuna, 2010), travelling distance to trees, understory density and terrain slope (Carey et al., 2018) can impact the productivity of motor- manual felling. Wider spacing between trees can increase the tree size, which will then result in higher felling productivity (Leite et al., 2014). When eucalypt stands are well treated, especially in the plantations, there is less understory. There would be also less hang-up when felling trees due to fewer branches and better crown form in well-treated stands. The stump diameter could vary from 10 cm to 30 cm. These suitable conditions could increase the productivity of felling (FAO, 1974).

Table 1. Summary of motor-manual productivity case studies in eucalypt stands

Continent	Country	Terrain slope	Tree size (m^3)	Variables impacting productivity	Productivity (m^3/ PMH_0)	Reference
Africa	Tanzania	Flat	N/A	DBH	7.7 (experienced operator) 6.2 (start-up operators)	Dos Santos et al. (2014)
Asia	Thailand	Flat	0.1	Travelling distance to tree, DBH	1.7- 4.1	Manavakun, 2014
Asia	China	20-52%	N/A	DBH	0.6	Engler et al., 2016
Oceania	Australia	Flat	1.5	DBH	48.9	Ghaffariyan, Acuna (2010)
America	Brazil	N/A	N/A	DBH, Experience, triceps/body fat composition (%) and body mass index (weight/height)	1.3- 2.2	Malinovski, Piovesan (2000)
	Brazil	N/A	N/A	DBH	5.2	Fernandes et al., (2013)
	Brazil	Flat	0.3-0.4	Tree size, planting spacing	4.7-5.73	Leite et al. (2014)
	Chile	13	0.1	DBH, Stem volume	1.2-1.3	Carey et al. (2018)

Results of previous studies also indicated that providing training and gaining longer work experience would help improving the felling productivity (Dos Santos et al., 2014; Manavakun, 2014). Some of the operational delays in motor-manual felling occurred due to waiting for the extraction machines to skid the felled trees to the landings (Ghaffariyan, Acuna, 2010). This type of delay could be minimised by applying a better work plan and an efficient harvesting management through allocating the logging crews and machines to the specific sites. Research findings in this review are consistent with other felling studies on Fageto- carpinetum stands in Northern Iran (Ghaffariyan, 2007), Appalachian hardwood trees in USA (Wang et al., 2004) and pine plantations in Uganda (Balimunsi et al., 2011).

This review article could be used as a guide to predict and control the motor-manual felling productivity in eucalypt stands. The number of studies on motor manual felling in eucalypt stands are limited and could be increased by carrying out more case studies in different stands and operations in various countries growing eucalypts. This, in turn, could provide more accurate estimate of the felling productivity. Future research could also explore the ergonomics (e.g. works stress and strains) and environmental impacts (e.g. emissions) of motor-manual fellingor could also develop a benchmark or review of felling productivity studies in coniferous and other hardwood stands.

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